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Diesel's Rational Heat Motor.

A LECTURE BY

RUDOLPH DIESEL.

New York.
PROGRESSIVE AGE PUBLISHING COMPANY.
1897.

SINGLE CYLINDER DIESEL MOTOR, 20 H. P.

DIESEL'S RATIONAL HEAT MOTOR.*

Our German contemporary, the *Zeitschrift des Vereines Deutscher Ingenieure*, contains a lecture delivered by Rudolph Diesel at the general meeting of the society at Cassell, held June 16, 1897. As we are convinced of the great interest American engineers are taking in the scientific advancement and practical development of the gas-engine, we deemed it advisable to furnish the readers of PROGRESSIVE AGE with an exact translation of said article, including reproduction of cuts and accompanying tables. After some introductory remarks, Mr. Diesel continues as follows:

In regard to the high state of development of the steam-engine of to-day, it is a generally known fact that in the best triple expansion steam-engines of over 1,000 horse-power, from 12 to 13 per cent. only of the whole heat contained in the fuel is converted into actual work; only 9 per cent. from smaller double expansion engines down to 150 to 200 horse-power; 5 per cent. from small engines down to 50 horse-power, provided condensation is used, and far less from the smaller steam-engines and those without condensation.

We all know the steam-engine to be one of the most perfect instruments of modern industry, brought to that height by our most able men having shown their best of talents in its development.

In view of this fact, the figures given are exceedingly low, nearly incomprehensible, and although this is generally known, we should be reminded of it as often as possible, referring to such work, for example, as the researches of Zeuner and Schröter. First of all, the moving power, steam, receives but a fraction n_1 of the caloric value H of the fuel; n_1 is the efficiency of the boiler, usually 75 per cent., occasionally 80, but never more than that. Furthermore, according to theoretical results, only a portion n_2 of the whole heat n_1H contained in the steam can be converted into work, which is generally very small, and reaches its greatest value when the steam is performing the Carnot or so-called perfect cycle. Here n_1n_2H would be the greatest quantity of heat convertible into work, provided the theoretical cycle would be attained. In practice, however, this theoretical cycle can be executed only approximately. The greater or lesser deviation of it necessitates a further loss of efficiency, for to Zeuner only a portion n_3, the so-called indicated efficiency is convertible into work, and, therefore, $n_1.n_2.n_3..H$ represents that quantity of heat which is transformed into indicated work. Finally, the steam-engine delivers at the flywheel but a fraction n_4 of the whole indicated work, the remainder being absorbed by the friction of the engine; n_4 is the mechanical efficiency, and the product $n_1.n_2.n_3.n_4.H=nH$ is the heat converted into effective work. Therefore, we call n the total or economical efficiency.

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* Translated from the "Zeitschrift des Vereines Deutscher Ingenieure" by Rudolph Leupold, M. E. Reprinted from PROGRESSIVE AGE (N. Y.) December 1 and December 15, 1897; January 1 and January 15, 1898; subsequent notes and illustrations of considerable interest appeared in the February 15 issue.

To fully understand the action of the steam-engine it will be necessary to consider the above four efficiencies separately.

The following table is compiled with regard to the best and latest results obtained from the most effective existing engines. For example, there were selected on the one hand a triple expansion steam-engine of 700 horse-power, constructed according to the latest design by the Augsburg Engine Works, and on the other hand a Schmidt superheated steam-engine, superheating to 350° C. (662° Fahr.), and a very high boiler pressure.

In both cases the boiler is assumed to have an efficiency of 0.80. Supposing the caloric value of the coal to be 7,600 thermal units (metric system), with this we should obtain more than nine times the evaporation, a result approachable only with large boilers of the best construction under condition of a very moderate working and close attention on the stoker's part.

The theoretical value varies between 30 and 33 per cent., according to the applied boiler pressure and degree of superheating. For this reason only the indicated efficiency n_3 of 59 or 60 per cent. is obtainable. With the same mechanical efficiency $n_4=0.85$ for both types of engines, the economical result varies between 12 and 13 per cent.

EFFICIENCIES OF THE BEST KNOWN MODERN STEAM-ENGINES.

Kind of engine.	Efficiency of boiler n_1	Theoret. greatest efficiency of the correspond. perfect process n_2	Indicated efficiency n_3	Mechanical efficiency n_4	Economical efficiency n
700 H. P. Triple expansion engine (built by the "Maschinen fabr. Augsburg") boiler pressure = 11 atm. absolute.	0.8	0.30 2122 calories per ind. H.P.	0.593	0.85	12.1
		Product of both 0.179, corresponding to 3576 calories per ind. H.P.			
76 H.P. Schmidt's superheated steam-engine; boiler-pressure = 13 atm. absol.; superheating temperature 350°C.	0.8	0.328 1940 calories per Ind. H.P.	0.592	0.85	13.1
		Product of both 0.194, corresponding to 3281 calories per ind. H.P.			

It can readily be seen that superheating even to the highest limit of 350° C. scarcely effects an improvement in comparison with the best nominal steam-engines, without superheating, as the Augsburger and Sulzer engine, provided the same boiler pressure of 185 pounds per square inch is applied, would have reached the same efficiency, which at present we must consider a limit scarcely to be surpassed, for the steam-engine of to-day has reached the limit of its highest development, as a further perusal of the tabulated values will show at once. The two values n_1 and n_4, the efficiency of the boiler and the mechanical efficiency of the steam-engine, can hardly be increased, as they already represent a very high degree of perfection. The indicated efficiency n_3 from 59 to 60 per cent. is very low in comparison with hydraulic engines. There may yet be an improvement in this which, however, can hardly amount to a great deal, owing to the tendency of steam to condense and its sensitiveness on coming into contact with metallic surfaces when in a superheated state. Besides, this improvement would not count much in view of the inexcusable fault of the steam-engine allowing only 30 per cent. of the heat to be transformed into work, assuming that even the perfect or Carnot cycle could be attained.

Summing up these radical faults we have: 1. The use of steam, the generation of which alone involves a loss of 20 to 30 per cent. of heat; 2. The inefficient theoretical process; 3. The great sensitiveness to condensation of steam in its contact with the metallic surfaces of steam pipes and cylinders.

Therefore, we cannot wonder at the greatest efforts being made everywhere to-day to discover a better means for the utilization of fuels, and that the solution of this problem must be regarded as one of the most advanced problems in modern technics.

I have been working on this problem during the past fifteen years, and tried, first of all, the application of vapors, which under normal conditions are far from their point of condensation, in order to reduce their sensibility against the effect of contact with the walls; for this purpose ammonia vapors were selected highly superheated in order to intensify the mere theoretical process by the use of the greater deviation of temperatures; therefore, I aimed at an increase in the values n_2 and n_3 in the foregoing table and constructed an ammonia motor which showed a striking difference of fuel consumption when superheating was applied.

From the vast amount of experimental and theoretical material collected on this occasion, it could easily be seen that highly superheated vapor can only be utilized rationally on condition of having at their disposal a reasonably great difference of pressure, enabling them to expand, for without it the vapor at the end of the expansion period remains superheated, and thus it is possible that a portion of its surplus heat is carried off. In each case it is possible to determine theoretically the amount of pressure necessary for a rational superheating, and it was observed that with highly condensed superheated vapor, pressures of 50 and 60 atmospheres would be necessary. Under these circumstances great difficulties are encountered in operating with ammonia and other vapors, and the endeavor to replace them with something cheaper and more easily manageable led to experiments with air. The theoretical research resulted in identically the same results; here also a theoretical deviation of pressure is necessary, corresponding with the utilization of a wide deviation in temperature. These two conditions are inseparable.

I had previously kept the working medium enclosed in vessels, and the heat was imparted to it from outside by means of heating, and taken away by means of cooling. This I still adhered to when I applied air, until the idea struck me that use might be made of the air, not only as a working, but simultaneously as a chemical, medium, thus rendering it feasible to do away with n_1 (efficiency of steam boiler or working apparatus) to a more or less extent. Thus I had arrived, in a round-about way, at an idea which had long ago been worked out in gas and hot-air engines, namely, the combustion of the fuel in the cylinder itself. Accordingly, in the course of developments I succeeded in arriving at the conditions for such a combustion, securing a better utilization of heat than heretofore. I published my ideas in a little book (entitled "Theorie und Construktion eines rationellen Wärmemotors Zum Ersatz der

Dampfmaschinen und der bis heute bekannten Verbrennungsmotoren"; von Rudolph Diesel, Ingenieur, Berlin, Julius Springer) which is here referred to. Permit me to briefly recall the four rules laid down, in pursuit of which a slight deviation from the main subject seems to be advisable.

In every process of combustion two kinds of temperatures are to be distinguished.

1 The temperature of ignition;

2 The temperature of combustion.

The temperature of ignition is that temperature to which a fuel must be heated to ignite it in presence of air.

The temperature of combustion is that temperature subsequently generated by the chemical process of combustion after ignition has taken place.

A somewhat trivial but striking example of this is the common match; its temperature of ignition is the temperature created by the friction at the surface, being only a little over the temperature of its surroundings. Immediately after the ignition has taken place a very high increase of temperature up to 600, 800 and more degrees C. is caused by the combustion.

The temperature of ignition is a constant value, and only dependent on the physical qualities of the fuel. It is very low for most fuels, and the higher the pressure at which ignition is effected the lower the temperature. Experiments conducted on that subject have resulted in astonishingly low temperatures. On the other hand, the temperature of combustion is a variabie value, being dependent on many conditions, especially on the quantity of air by which the combustion is maintained, and which under all circumstances is higher than the temperature of ignition.

In all combustions hitherto known, only one proceeding was recognized, namely, the generation of the combustion temperature by the process of combustion after ignition has taken place.

FIRST CONDITION.

In my book I pointed out the most important and fundamental principle: that the combustion temperature must be generated not by the combustion and during the same, but before and independent of it after ignition had taken place, by mechanical compression of pure air. Although this idea seemed to be contrary to common sense, it nevertheless meant an entire revolution of the then prevailing opinion on combustion; however, it is only a realization of a condition which has long ago been demanded by the theory of the perfect or Carnot cycle without having succeeded in finding a practical development for its utilization. It fact, it must be declared that the realization of the theoretical facts of the Carnot cycle necessitates the overcoming of great difficulties on account of the high pressures involved in it.

SECOND CONDITION.

For that reason I set forth a second condition of rational motor combustion, that is, to deviate from the perfect process by directly compressing the air adiabatically instead of first isothermally from 2 to 4 atmospheres and then adiabatically to the 30 or 40 fold. By so doing one realizes the first of the required conditions, *i. e.*, the generation of the combustion temperature by mere compression with pressures which are two and four times lower than those used in performing the perfect cycle. For instance, the pure Carnot process would require pressures of 100 and more atmospheres, in comparison with which the deviated process proposed and executed by me only demands 30, 40 or 50 atmospheres in order to reach the same high ignition temperature by compression. In fact, this deviation of the perfect process represents the only possibility of replacing the perfect process which is not practically attainable.

THIRD CONDITION.

The third condition of rationally conducted motor combustion set forth is: That the fuel must be introduced gradually into the air which is compressed adiabatically to the combustion temperature

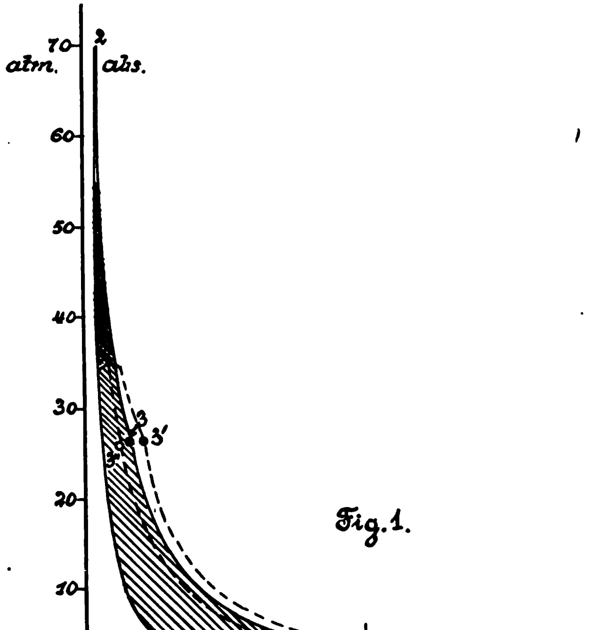


Fig. 1.

THEORETIC DIAGRAM.

in such a manner that the heat generated by gradual combustion is absorbed in the so-called nascent state, in consequence of a corresponding expansion, *i. e.*, by mechanically cooling off the gases so that the period of combustion is going on constantly isothermally. It is evident that the fuel, in order to fulfill that condition, must be changed in its physical composition to a gaseous, liquid or powdery form.

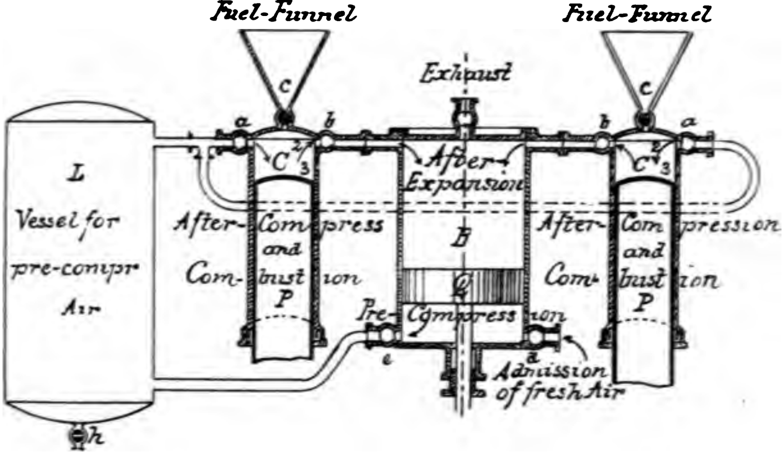
That is to say, that through the combustion and during the same, no, or a relatively small increase of temperature is caused, an idea which seems to be absurd after having heretofore always effected the increase in temperature by the combustion and during the same.

FOURTH CONDITION.

The fourth condition also presents a revolution of ideas hitherto considered correct, according to which the combustion had to be carried on with as little surplus of air as possible, while I contend that a considerable surplus of air, whose amount can be determined theoretically in each special case, is necessary.

The four conditions pointed out represent a process of working for combustion engines, made clear in the theoretical diagram Fig. 1. In reference to it, pure air is compressed in the cylinder according to the curve 1 to 2, so that by it alone (before combustion and independent of it) a combustion temperature is effected whereupon the fuel, according to curve 2 to 3, is so gradually introduced that the combustion is going on isothermally, on account of the piston's motion taking place, and the expansion of air thereby effected without materially increasing the pressure. After the supply of fuel has been shut off, the gas in the cylinder will further expand from 3 to 4 as shown in the curve.

Fig. 2.



SCHEMATIC REPRESENTATION OF THE DIESEL MOTOR.

It need not be mentioned particularly that in practice the narrow part 2 of the diagram will not come out so pointed as in theory; it will assume a rounded-off form; neither will the different curves run exactly according to the theory, and the curve of combustion may more or less deviate from the isothermal curve without changing the nature of the process.

The great advantage of omitting the long stretched out extremities at 2 and 4, they not having any value worthy of mention, is evident. On the contrary, by doing away with them we succeed in obtaining at 2 far less, and consequently more practical heights of compression, and at 4 smaller cylinder dimensions. Therefore, it will be advisable to cut off these attenuated extremities, as shown by the dotted lines, and thus obtain the real diagram, shown by the lighter hatched portion of the finished engine, such as was really obtained from the experimental engine.

Fig. 1 shows how such a diagram, and consequently the efficiency of the engine, may be regulated. The shape of the combustion curve is changed from 3′ or 3″, as shown by dotted lines, by changing the duration of the fuel supply; thereby also altering the expansion line following after it. It is also permitted to change the total height of the diagram and, therefore, also its area by introducing the fuel at various points on the compression line, as designated by dotted lines.

In the former publications referred to, according to the theoretical foundations of the conditions just set forth for a really motoric combustion, a series of designs is proposed, all realizing these conditions as far as practice is concerned. Such a rationally working heat motor is represented by Fig. 2. The valves therein are but crudely indicated, and foundation, connecting rod, flywheel, etc., are omitted. There are also two combustion-cylinders C with plunger P, the details of which are adapted to stand high pressures, especially in regard to the piston packing. By means of geared valves b both these cylinders C are connected to the two sides of a larger intermediate cylinder B; the combustion cylinders communicate, by means of the geared valve a, with the air vessel L. The cranks of both cylinders have the same position and advance 180° with regard to the intermediate cylinder crank.

When piston Q moves up it draws air through the valve d, which is compressed during the downward motion to several atmospheres, whereupon it is forced through the valve e into the air vessel L. The lower part of the intermediate cylinder only serves as an air pump and brings about the precompression of the combustion air. This precompression, however, is to be effected only so far that the heating of the air thereby caused is kept within a moderate limit.

During the downward stroke the piston P draws air already precompressed from the vessel L.

In its upward motion the piston performs the second period of compression to the required height. The extreme lower and upper positions of the piston are indicated by the dotted lines.

Hereupon the piston again moves downward to position 3, during which period fuel is gradually being introduced and consumed as previously explained. In this case the fuel is used in the form of coal dust which is admitted to the cylinder during a prescribed admission period by slowly turning a rotating cock provided with a small lateral groove.

At 3 the fuel supply is shut off and the expanding of the air is continued. The piston having reached the lower position 1, valve b is opened; at this very moment piston Q is in its upper position; by continuing the action P goes upward and Q downward, the gases of combustion expanding further on to the volume of the cylinder B. Hereupon valve b is closed and f opened; the combustion gases are then expelled into the open air at the next upward stoke of the piston Q.

As the cylinders C have at every second revolution only one combustion period, by the arrangement of the two cylinders, a combustion at each revolution is effected, *i. e.*, one working period is taking place alternately at right and left.

When we glançe at the Table I, it can readily be seen how such an engine must be superior to a steam-engine. First of all, owing to the immediate combustion of the fuel in the cylinder, no steam boiler is necessary, n_1 becoming = 1. Furthermore, the greatest theoretical efficiency n_2 is for the new motor as has been proven equal to 50 to 70 per cent., *i. e.*, an average of more than twice as much as that of the best and largest steam-engines. The indicated efficiency n_3 likewise will become considerably greater as we have not to deal with condensable gases, and many other sources of losses have been abolished. It was to be anticipated, however, that the mechanical efficiency would result in a lower figure, on account of the high compression that is involved in negative work. Henceforth this was the point that had to stand the energetically conducted attacks of criticism, which endeavored to demonstrate by calculation that this mechanical efficiency would be found such a low one that the fully recognized theoretical advantages might not be realized, and the motor give lower practical results than all others formerly designed.

			Left combustion cylinder, single acting, working according to the four-cycle process.	Intermediate cylinder, double acting; pre-compression below; after-expansion above.	Right combustion cylinder, single acting, working according to the four-cycle process.
4-cycle or 2 revolutions.	1st revolution.	above	Suction of compr. air from the intermediate vessel.	Exhaust.	Combustion and beginning of expansion.
		below	———	Suction of fresh atm. air.	———
		above	After-compression of air.	After-expansion from right combustion cylinder.	Transferring to the interm. cylinder and simultaneous after-expansion.
		below	———	Pre-compression of air in interm.	———
	2d revolution.	above	Combustion and beginning of expansion.		Suction of compr. air from interm. vessel.
		below	———	Suction of fresh atm. air.	———
		above	Transferring to the interm. cylinder and simultaneous after-expansion.		After-compression of air.
		below	———	Pre-compression of air in interm. vessel.	———

Position of cranks, all in the same plane.

The theoretical advantages of the rational system were so important that their realization was considered by many authorities as worthy of exhaustive investigation. In my researches I was especially assisted by Professor Zeuner,the head master of technical thermodynamics, by my respected teachers, Professors Linde, Slaby and many others. Men in industrial circles were also found who were willing to sacrifice time, labor and money for the investigation and proof of this scientific problem. The first to do so was Herr Buz, director of the *Augsburger Maschinenfabrik*, who was later on followed by Fried. Krupp, Gebrüder Sulzer in Winterthur and Carels Frères in Ghent. A laboratory was built at Augsburg, provided with all the means for scientific and technical research adapted to the conducting of systematic experiments.

The procedure was as follows: The making of a single-cylinder motor, consisting of the combustion cylinder only, shown in Fig. 2, to perform in it the process of combustion, and to study the constructive details; thereby less difficulties were to be overcome than if three cylinders (as shown in Fig. 2) had been adopted at first. Furthermore, by so doing an engine was constructed representing a commercial value for small and medium sizes, on account of its simplicity. The compound motor, which was to carry out my ideas, and which certainly predicted much better results, was to be built after the single-cylinder engine had been accomplished. It was furthermore determined that the experiments were to be conducted first with liquid, then with gaseous, and afterwards with pulverized fuel. It may here be mentioned that the idea prevailed from the beginning that the generation of gas from coal would be simpler and cheaper than its crushing and sifting, and that the application of coal dust, although it seems to be very tempting from the first, would offer disadvantages, rather than advantages, as compared with the use of gas.

Based on this fixed program, the engine represented in Fig. 3 was built. It shows a motor with a single-acting cylinder C and plunger P, whose details are constructed to stand high pressures. Piston P is connected to the flywheel axis d by means of cross-guide a, connecting rod b and crank in the usual manner. By means of bevel wheels the flywheel shaft turns the inclined shaft g, which revolves the gear shaft W. On this shaft two cams are fastened, opening respectively the air valve V and the petroleum valve D at a specified moment. This latter gearing is fully shown in Fig. 3; that for the valve V performs its work in a similar manner. Both valves are forced on their seats by means of springs as soon as the cams release.

The process in cylinder C is carried on in accordance with the four-cycle period, as follows:

First: Downward motion of the piston P, caused by the *vis viva* of the flywheel which was received from the preceding work stroke. Atmospheric air is drawn through the opened valve V into the cylinder C; the lowest position of the cylinder is designated by s.

Second: Upward motion of the piston P, still caused by the *vis viva* of the flywheel, the valve V being closed. The air drawn in the cylinder is compressed to such high pressures that the temperature at which the combustion following same is going on is generated by this compression alone. This compression-pressure can only be caused by the piston P, after having, in its end position, compressed the air drawn in to the required temperature.

Third: Second downward motion of the piston P, or proper working stroke, follows. The introduction of fuel takes place during the motion from position 2 to 3 of the piston, by the little pump A, operated by several projecting cams N, N_1, N_2, regulating the required periods of fuel supply. In position 3 the admission of fuel is shut off and the air expands until the piston reaches the lower dead centre.

Fourth: Second upward motion of the piston P, due to the *vis viva* of the fiywheel; the gas is expelled through valve V to the outer atmosphere. After this second upward motion the operation is repeated.

The motor is started by admitting air through a proper valve from a storage tank, the latter being constantly filled with compressed air while the engine is working. It may be noted here that the engine was run without a cooling jacket, thereby proving the possibility of working without cooling water, as was theoretically anticipated. In later constructions the cooling jacket for practical reasons was added, which permitted greater effects to be obtained from the same cylinder dimensions. From the numerous results based on the experiments, I arrived at the conclusion that the opinion, that the water jacket is the only obstacle in realizing greater efficiences, is erroneous. With all caloric motors, the carrying away of a certain amount of heat is necessary from a theoretical standpoint. In the steam engine a special apparatus, the condenser, is provided for this purpose. In combustion motors the condenser is represented, on the one hand, by the cooling jacket, and on the other, by the atmosphere, which receives the heat of the expelled gases. Both quantities of heat carried off—provided certain loses, generally lower than suggested, are not taken into consideration—represent those quantities of heat to be taken away, in order to perform the process in the right way. Therefore, the water jacket is no irredeemable fault, but a theoretical necessity, as the condenser is in the steam engine. The numerous efforts to save, as far as possible, the heat that is carried away are incomprehensible, and their failure to do so is evident. This effort resembles the tendency to save heat in steam-engines by introducing as little cooling water into the condenser as possible. If one is desirous of saving the heat carried away, there is only one means, *i. e.*, to choose such a process of combustion at the start that from a merely theoretical standpoint a less loss of heat is necessary. It would take too long to prove this opinion, but it is based on accumulated experimental facts.

As the new process necessitates high compression-pressures with simultaneous high temperatures, so many new and high claims were attributed to it that only little remained of former experiences to depend upon; nearly every single detail had to be adapted to its special purpose by tedious study and continuous building and rebuilding. I will omit entering upon the question of the numerous valve, piston and gearing constructions, materials and many other things. Great difficulties were to be overcome in the supplying of the fuel, because it was to be introduced in small quantities, in an exactly regulated manner, by strong and durable apparatus. It required two years of investigation and testing before it was possible to undertake the rebuilding of a new motor which was to include all former experience and which really would be fit for practical use. This second experimental motor of 12 horse-power was necessarily very imperfect, as the greater portion of it was composed of older details which were not yet thoroughly worked out. Nevertheless, the results obtained from this engine in the latter part of 1895 placed it instantly at the head of the caloric motors then in existence. The communication of these results is unnecessary, as they are far surpassed by newer constructions. It need only be mentioned that this motor was tested while furnishing the power for a factory for periods of several months, working equally as well with petroleum as with illuminating-gas.

Based on these actual facts, a new motor of 20 horse-power was built, which in the beginning of 1897 was tested with petroleum, and upon which the following data are presented:

The engine is shown by Figs. 4 to 7. From this can be seen that the cylinder, for the reasons previously explained, is provided with a cooling jacket; that the plunger with oil stuffing boxes is replaced by a ring-piston; that the gear shaft has been extended to the top; that suction and exhaust valves are separated, etc. The small air pump Q, driven by connecting rod Z and lever X, keeps the vessel L filled with compressed air under a higher pressure than the highest compression attained in the cylinder, and is a new detail. By means of the pipe connection S, the same excess of pressure is connected with the interior of the injection valve D. In it the petroleum is collected during the intervals in the four-cycle period between the combustion periods. This petroleum is introduced by a little pump, not shown in the figure. By opening the valve stem n, the fuel is by its high pressure caused to flow through the nozzle opening D to the combustion chamber of the engine, thus creating the combustion period in accordance with diagram 1, wherein the form and length of the combustion line can be altered according to the performance of work, partly by changing the regulation of the fuel supply, partly by changing the excess of pressure in the vessel L and finally by performing the injection at different points on the compression line, as previously demonstrated.

Fig. 7 shows in detail the entire gearing, and especially the starting of the motor by the compressed-air vessel L. W represents the gear shaft with a number of cams, I to V.

Cam I operates the valve V_1, III the fuel-valve in the nozzle D, and V the exhaust valve V_2 of the engine. The whole of the gearing also serves to start the engine by passing compressed air from L through the valve Y (Fig. 4) to the cylinder, pushing the piston ahead and escaping through the main valve V_2. During this very short starting period the lever H (Fig. 7) is in the position H_1, so that the valve Y is geared by cam II, valve V_2 by cam IV (instead of V), while fuel plate III and cam I of the admission valve are disconnected. After a few revolutions the engine obtains its normal speed. At this moment a pin d (Fig. 7), keeping the lever H in position, is removed, and the latter is automatically, by means of the spring F, snapped into its normal position H, and with it the five cams, and thus the normal running is effected without interrupting the working of the engine, already brought about. The engaging of the cams at the right moment can only take place if a notch, especially provided for that purpose in the cam system, passes before the lever p.

After having touched upon the development of the construction of the new motor, the development of the operation may be shown by the diagrams obtained from tests made during a period of several years. As the diagrams are intended to represent the development only, it is unnecessary to mention the scale to which they are drawn (Fig. 8.)

These diagrams have been made partly by benzine, petroleum or gas; partly by vapors of liquid fuels, and partly by mixtures of liquid materials with gas. It would go too far to enter into all these details; for the same reason, it is impossible to demonstrate by which peculiar means the diagrams have been obtained. There are generally six distinct periods, among which a specific general evolution is noticeable. Within each period we can again discern sub-periods, corresponding to certain alterations or reconstructions of the engine. It would be useless and, at present, without interest to describe all the arrangements that have during the course of time accumulated.

I. PERIOD, 1893.

No. 1. The first diagram actually produced was accompanied by very violent explosions and destruction of the indicator. The same accident has often occurred during the time of the development of the engine; so far all trials were connected with great danger, and the decision to try new arrangements was difficult to arrive at, and was often reached only after weeks of discussion.

I desire to thankfully acknowledge the assistance of Messrs. Lucian Vogel and Fritz Reichenbach, engineers, with regard to the development of the new motor. They devoted themselves to the experiments with never-failing perseverance, and thus most successfully advanced the work.

At the present time the combustions in the cylinder take place smoothly and with certainty, and are entirely controlled by the governor, so that, during the easy running of the engine, one can scarcely perceive the beginnings of the power stroke. In addition to that, it is worthy of mention that during the many years of the experimental period not one accident has happened to any one of the attendants.

Nos. 2, 3, 4. Eliminate the explosions, but show no real development. In this first period, idle running of the engine was not yet effected; it was only proved that combustions were obtainable according to the proposed proceedings.

Then followed an entire reconstruction of the motor.

II. PERIOD, 1894.

Nos. 5 to 12. Through many failures a marked combustion-period was gradually generated, in the beginning, very restless, then quieter (10 to 12), but never any real development of the diagram. Nevertheless, quiet running was obtained, and thereby it was proved that the achievement was possible, although very little had as yet been accomplished. In addition to that, several diagrams showed quite correct development and large increase of work, but they were obtained only occasionally, and the conditions of their repetition could not be determined.

III. PERIOD, 1894.

During this period the ignition of the fuel was tried by means of kinematic arrangements, having for their purpose to make the quantity of fuel to correspond to the travel of the piston, according to theory. This apparently correct idea led to entirely misleading results. During a period of ten months we obtained, in spite of all rebuilding, only such diagrams having the appearance of Nos. 13 and 14, without any areal development. This period was the most unsatisfactory during this entire course of experiments, and entire faith of all interested in the scientific truth which guided us was all that kept the experimenters from abandoning the whole matter at that time.

IV. PERIOD, 1894.

Entirely abolishing the III period, diagram No. 8 of the second period was resumed. As it could be generated occasionally, it would have to be often repeated. We succeeded in so doing, as proved by diagrams 15 to 18, whose combustions, already showing an increase of work, were, however, going on very irregularly, and many failures happening.

V. PERIOD, 1895–6.

Nos. 19 to 22 still show a real development and increase of diagram, but combustion is still irregular. Nos. 23, 24 and 28 finally show good quiet developing of the diagrams. The motor was run through a period of several months, accompanied by thermal results which even at that time far surpassed those obtained by any existing similar motor. Diagram 27 is obtained after the fuel supply has been shut off; it is to be seen that compression and expansion line nearly coincide. No. 29 is a starting diagram. The starting has been effected by means of compressed air. After the reversion of the gearing a number of normal diagrams at full capacity is visible. Nos. 30 to 33 show several endeavors to change the fuel supply, but they did not give good results.

VI. PERIOD, 1897.

The typical diagrams of the petroleum motor, to-day entirely developed, are here shown, as determined by Professor Schröter. No. 35, taken under normal conditions, shows the compression line. The top, which is rounded off, shows the combustion as taking place isothermally, and the expansion follows. No. 34 represents the successive relief from full load to almost zero. The decrease of the diagram, by shortening the admission period of the fuel, is shown, as is the case in steam-engines, when the decrease of diagrams is effected by less admission. This diagram shows one of the most valuable qualities of the motor—its entire similarity to the steam-engine in regard to form of the diagram and regulation.

Here one must not be deceived by the scale, as the diagrams still appear very narrow. Their true meaning is to be seen from Fig. 9, in which the diagram of the steam-engine, of the explosion motor and the rational motor are drawn for the same cylinder volume in the same scale; it is evident that the diagram of the new motor is by far the largest as to area. Diagram 36 is taken at half load. Diagram 37 is the diagram of the air pump. In this period and with these diagrams results were obtained, upon which a report will be made later.

The most extensive experiments were made with this motor, partly by professors and partly by representatives of industrial establishments, as follows:

February 4 and 5, 1897; by Messrs. Schumm, superintendent, and C. Klein, engineer of the Deutz Gas-motor Works, and Mr. Gillhausen, chief-engineer for Fried. Krupp in Essen.

February 12 and 13, 1897; by Messrs. Sulzer-Imhof, Sulzer-Schmidt and Eric Brown, of the firm of Sulzer Brothers, in Winterthur.

February 17, 1897; by Professor Schröter, of the Technical College of Munich, assisted by Dr. Munkert and Engineer Brückner, both of the same college.

March 17, 1897; by Prof. M. F. Gutermuth, of the Technical College of Darmstadt, assisted by Engineer Richter, of the Nuremberg Machine Company.

April 30 and May 1, 1897; by a French committee, consisting of Messrs. E. Sauvage, professor at the national school of the University of Paris, and engineer-in-chief of mines; E. Carié, chief engineer of the Mediterranean Iron and Construction Works; G. Merceron, superintending engineer of the Meusienne Railway Company, and Fréd. Dyckhoff, constructing engineer in *Quai le Duc*.

All of these trials were carried on with the greatest accuracy, with repeated examination of all apparatus and instruments used, and with absolute conscientiousness. They lasted at times one, but mostly several days, and embraced all working conditions of the motor and its regulation under all complicated conditions.

The results of all trials agree to such an extent that they can be considered reliable, and through them the new engine is placed at the head of all motors built to the present time, surpassing them all with regard to the utilization of heat. Professor Schröter has kindly consented to report on his tests, and as is customary with his work, these tests can be regarded as a classic standard of accuracy and perfection, therefore, I am relieved of the task.

Referring to the first table, giving the efficiencies of the best known modern steam-engines, we will at once be struck by the following facts:

First: The efficiency of the steam boiler n_1 is in the new engine equals 1, as the whole combustion heat of the fuel is transferred to the working body, air.

Second: The theoretical efficiency n_2 varies, as I have proven for several instances, from 50 to 70 per cent.; the smaller value corresponds to the simple single-cylinder engine represented in Figs. 4 to 7, and which, on account of its simplicity, has a very extended field of application; the larger value corresponds to more complicated arrangements, especially for compound system, which I consider to be the only correct construction for those engines aiming at the utilization of heat. This value n_2 is twice as much as that of steam-engines, and represents the superiority of the new motor over steam-engines and explosion motors, whose value for n_2, according to Clerk, varies from 33 to 43 per cent.

Third: The actual indicated work varies, according to experiments, from 34 to 40 per cent.; the indicated efficiency of this simple engine n_3 is thus 70 to 80 per cent., consequently, it is by far superior to that of the steam-engine, and materially higher than that of the explosion motors.

Fourth: The mechanical efficiency n_4 of the new engine, varying between 71 and 75 per cent., is, therefore, materially less than that of the steam-engine and explosion motors. It cannot, however, be denied, and there are good reasons for the supposition that the mechanical efficiency may be gradually increased to that of other engines. Be that as it may, for the present we only have to consider facts, and these give the economical result, which is:

$$n = n_1 . n_2 . n_3 . n_4 = 1 \times 0.50 \times 0.72 \times 0.74 = 0.266,$$

i. e., 26.66 per cent. of the total heat is converted into effective work.

As the fuel used for the experiments was usually refined petroleum, a comparison with motors of this kind only is permissible.

Fig. 10 shows the most reliable experiments published in Germany, graphically represented (by Prof. W. Hartmann), up to the present time. The abscissae represent the stroke volume or piston displacement in liters per second, the ordinates the petroleum consumption in grams per hour, both for a brake horse-power, the solid lines corresponding to full work and dotted to half work. The names of the respective engines are written near the several points on the curves.

From this figure we learn two other qualities of the new engine. The first is, the very small increase in fuel consumption while the work is decreasing.

It can almost be expected that the consumption per horse-power, within the limits of the engines in practical use, is nearly constant, while with all other petroleum engines it increases enormously during diminution of load. This peculiarity is explained by the very strong increasing thermal efficiency accompanying decreasing work, whereby the loss of mechanical efficiency during less work is, to a greater extent, counterbalanced. No other engine has this peculiarity, not even the steam-engine, and this is of vast importance; in practice, an engine never works with its highest load, and, therefore, in reality, never keeps up the results obtained during tests, nevertheless the new engine is actually accomplishing this.

The second of the valuable qualities set forth by Fig. 10 is its small dimensions, as compared with the explosion motors constructed up to the present day. It is to be seen that at full work the cylinder dimensions of the most successful of the motors are 50, 60 and even 100 per cent. larger than those of the new one, supposing, of course, all motors to have the same number of revolutions, as indicated by the diagram. This is proven, without question, by Fig. 9, rendering conspicuous the diagram of the steam-engine (ocean grey-hound "Fürst Bismarck"), of the petroleum explosion motor and the rational caloric motor. It is evident how the tendency prevails to draw out the diagram from the corner of the co-ordinate system into space. From the fact that the diagram of the new motor has, by far, a greater area than that of the explosion motors, its mean pressure is respectively greater, and the dimensions of the engine are smaller for the same work. The immediate consequence of this is that the piston, connecting rod, flywheel axle, etc., of the rational motor can be built not stronger, but weaker than those of the same capacity explosion motor. These facts annihilate the most important of the objections brought into the field against the new system, viz., that the dimensions would be so great as to be impracticable.

A third material advantage of the new motor is visible from the regulating diagram. No. 34 (Fig. 8), which shows that the work can be regulated exactly as with steam engines, by changing the oil supply, *i. e.*, the admission period. According to the work done the diagram becomes narrower or broader (for the actual scale see Fig. 9), and, indeed, the engine is controlled in an astonishingly exact manner by the governor, as the loading and unloading of the engine during the trials have proven. This has never been known to fail. This method of regulating makes the new engine of equal importance, as to elasticity of operating, smoothness and uniformity of running, to the steam engine, and does away with the more material disadvantages of the explosion, a proceeding whose shock-like action and regulation by projecting parts was one of the most important hindrances preventing its extension into the field of steam-engines.

A fourth very valuable quality of the new motor is its continual readiness for service. As stated before, the motor in the condition that it was when last put out of action, and after an indefinitely long pause, is ready for starting without any heating or preparations of any kind whatever.

The fifth and, perhaps, best quality of the engine is the entire absence of interior soiling after continuous long service, due to the perfect combustion under conditions arising from the process. From this it also follows that the exhaust gases are entirely invisible and nearly odorless during the greater period of running, and only become visible when the engine is very much strained.

Less material advantages, but, nevertheless, advantages of great importance, of the new engine are: The absence of any ignition apparatus, whether electric, by flame or by incandescence; the absence of lamps, generating or pulverizing apparatus, of mixing apparatus, etc., and, in consequence, its simple construction.

These peculiarities, making the motor equivalent to the steam-engine (but with the omission of boiler and appurtenances), are increased by its low fuel consumption, amounting to 250 grams (8.82 oz. avoir.) and less per brake horse-power hour, according to results obtained at normal working, and not when the greatest work is done.

It is important to note that the new motor gives about the same result whether large or small, and that, therefore, there is no reason to concentrate the power required to run a factory, as was necessary with the steam-engine, on account of the economy of the service and the simplicity of attendance. The principal requirements for the steam engine were: Utmost centralization and largest units. For the new engine the contrary will sometimes be recommended: Decentralization, small units, put immediately at the place of use, and the abolition of long and expensive shaftings or power transmissions which in many instances tend to a great waste of power. This principle of decentralization is especially important for the traction engine. Imagine, on railways, a number of single motor cars, instead of the long, heavy trains with locomotives, and it is easy to see what an immense simplicity in the many branches of the service can be achieved. On local trains the whole service might be conducted in this manner. On main line railways the forwarding of mail, baggage, many freight and certain passenger trains could be run separately from the through-train service.

Although the new motor may be regarded entirely developed as a petroleum motor, its field is still more extensive. It has already been mentioned that the running with illuminating-gas was carried on just as successfully as with liquid fuel. Experiments to this effect have been made and the results can be produced at any time. The new engine will, however, first obtain its entire comprehensive importance when it is able to use common coal, and when it can be manufactured in units of 100 horse-power and more. In both directions experiments are being made by the machine shops at Augsburg; a large 150 horse-power motor is being set up, and a fuel-gas generator is already built. The experiments themselves, and the development of the engines and apparatus for this kind of service, necessitate, of course, a great expenditure of time; nevertheless a comparatively quicker solution of these questions may be expected, in view of the vast amount of experimental material accumulated during a period of many years.

The experiments conducted with the motor by Professors Schröter and Gutermuth and others have shown an indicated efficiency in the utilization of 34 to 35 per cent. of the heat contained in the fuel under normal conditions, and 38 to 40 per cent. at half work done; these figures are about 50 per cent. higher than the best indicated gas-engine efficiency obtained up to the present (attaining, according to Dugald Clerk, 27 per cent. in several cases, but generally remaining considerably below that figure), especially when taking into consideration normal conditions at varying and unusual loads.

In the figures representing the indicated utilization of heat, the great superiority of the new combustion process, in comparison with the heretofore applied combustion processes, is demonstrated, especially when we consider that the new process is placed on a level with a proceeding that has reached its highest degree of perfection, according to the opinion of the most esteemed men of the profession.

In applying a fuel-gas generator as previously mentioned, however, a loss of energy must be considered, due to the transformation of raw material. The fuel-gas generators do not give off all of the heat units contained in the coal, but only 80 per cent. of the amount, and they are, therefore, equivalent to our best steam boilers. Their operation, however, is very much simpler. It may be noted that there are many theoretical and practical reasons for the supposition that, at a time not far off, the gas-generators will give off 90 and even 100 per cent. of the heat contained in the fuel. In this direction the efforts of the engineers must be led; here is a productive and fruitful field of exploration, and there is no doubt but that the use of such a gas-generator with a rational caloric motor whose properties in operation are similar to those of the steam-engine will be the means of solving the question of replacing the steam-engine sooner than has been expected.

Moreover, one can imagine the facility of generating fuel-gas at a central station and distributing it compressed to 40 or 50 atmospheres in very small pipes to an indefinite number of motors, and immediately to the engines. In view of these figures and future prospects based chiefly on experimental results, the ability of development being founded on fixed scientific truths, it must be said that it is as much the duty of all the fraternity as of the single individual to check the wasting of fuel such as is going on to-day. An urgent appeal should be made to all whom it may concern, to consider this fact and the influence of scientific truths in the solution of this great problem, and to bear in mind Redtenbacher's words, when he wrote from 1856 to 1859 to Zeuner, that "the principle of steam generation and utilization is wrong; it is to be hoped that at a time, not far off, the steam-engine will disappear after we have acquired clear ideas on the nature and the effects of heat." The latter is the case to-day. Science has shown us the path which we must take, and business men, willing to make sacrifices, have proved that these ways are correct and lead to the point desired.

I take great pleasure in publicly expressing thanks to those who, after having been convinced by scientific facts, did not spare any pains in their endeavor to accomplish results with never-tiring perseverance. Especially, thanks and credit are largely due to Mr. Buz, superintendent of the Augsburg machine shops, and the firm of Fried. Krupp, in Essen, who not only furnished the material used, but also took the vast burden of the experimental work on their shoulders, and with keen foresight, never despaired of the final success of the correct principle, not even in the dark moments of invisible progress.

Since the lecture has been delivered, some improvements, reducing the petroleum consumption to 215 grams (7.58 oz. avoir.) per horse-power hour, have been developed, making the economical efficiency exceed 30 per cent.

TESTS MADE WITH DIESEL'S RATIONAL HEAT MOTOR.

BY PROF. M. SCHRÖTER.

The theoretic principles of Mr. Diesel's motor have been explained so clearly upon several occasions by himself that I only need to say that among the professional men there was only one opinion from the beginning, namely, that these theoretical principles are entirely correct and indisputable. As to the question of a practical application of the theory, the same unanimity did not prevail, but I feel greatly honored by the request of our president, to have the opportunity of proving to such a select group of professional men the fact, based on figures, that applied thermodynamics as applied to caloric motors is not impracticable, as has been so often asserted.

The motor which I tested is the first manufactured in the Augsburg machine shops. It was set up in a room especially adapted for testing purposes and provided with every means for facilitating the work. The arrangements were so excellent and perfect that I could use them instantly for my purposes and only needed to control the constants. The chief points in question were: The ascertaining of indicated and effective work, the petroleum consumption, the quantity required and heating of cooling water, and also the temperature of the exhaust gases. Preparations had been made also for the chemical determination of the latter and the ascertaining of the caloric value and the composition of the petroleum. These devices were checked up by repeating the corresponding examinations in the chemical laboratory of the Technical College, at Munich. For this portion I had the assistance of Dr. Munkert, professor of chemistry at the college; the other observations were made by Mr. Brückner, engineer and assistant of theoretical mechanics, and other assistants under my personal control. The results obtained are here given under the following heads:

I. INDICATED WORK.

The indicated work is performed partly in the working cylinder acting according to the four-cycle system, partly in the single acting air pump; the dimensions coming into consideration were as follows:

	Diameter of piston in millimet's.	Stroke in meters.	Piston displacement liters.	Ratio piston displacement	Constants.
Working cylinder	250.35 (9.84 in.)	0.3985 (15.86 in.)	19.62 (0.69 cu.ft.)	25.5	$\frac{F.\,s}{2\times 60\times 75}=0.021796$
Air pump.........	70.0 (2.75 in.)	0.20 (7.87 in.)	0.769 (0.027 cu.f.)	to 1	$\frac{f.\,s}{60\times 75}=0.0017105$

The high pressures in both cylinders necessitate the application of small indicator pistons. During the testing of the indicator-spring in the college at Munich the normal piston was applied as usual and the resulting scale was decreased according to the ratio of the piston areas. There were used two instruments; one a

Fig. 11

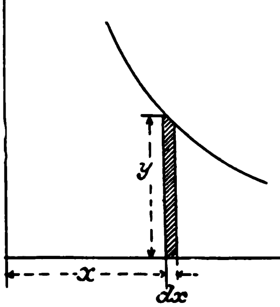
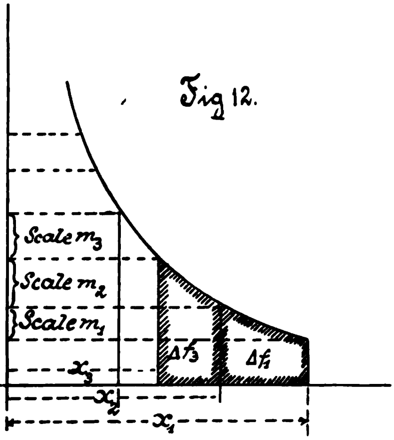


Fig. 12.



DETERMINATION OF THE MEAN SCALE.

Schäffer and Budenberg at the working cylinder, and another a Dreyer, Rosenkranz and Droop at the air pump; both worked perfectly. The examination of the spring, repeatedly done with great carefulness, resulted in a scale, decreasing with increasing pressure, so that to attain the greatest accuracy the simple arithmetical mean could not be taken, and the mean scale was found in the following manner:

If F denotes the area of the working piston, p the pressure per unit and m the scale at any point of the diagram, one obtains for the work the following formula (Fig. 11):

$$L=\int p\,dV=\int pF\,dx=F\int\frac{y}{m}\,dx$$

If m varies in such a manner that within certain limits of pressure sufficiently small constant mean values of m_1, m_2 may be substituted, the work is calculated by dividing the diagram with horizontal lines into such portions $\triangle f$ which have as unit a constant scale (see Fig. 12) according to the formula:

$$L = F\left\{ \frac{1}{m_1}\int_{x_2}^{x_1} y\,dx + \frac{1}{m_2}\int_{x_3}^{x_2} y\,dx + \ldots\ldots \right\}$$

$$= F\left\{ \frac{\triangle f_1}{m_1} + \frac{\triangle f_2}{m_2} + \ldots\ldots \right\} = F\Sigma\left(\frac{\triangle f}{m}\right)$$

On the other hand, if m_0 denotes the mean scale of the whole diagram, we have:

$$L = F\frac{\Sigma(\triangle f)}{m_0}$$

By solving both expressions by equating the value for L we obtain, therefore,

$$m_0 = \frac{\Sigma(\triangle f)}{\Sigma\left(\frac{\triangle f}{m}\right)}$$

We confine this calculation to an average diagram, *i. e.*, one whose area nearly equals the arithmetical mean of the sum of all the diagrams. Moreover, we will consider the expansion and compression period separately and find the mean scale for both from the mean scale of the whole diagram in the following manner:

Average scale of the expansion work: $m_0' = \dfrac{\Sigma\triangle f'}{\Sigma\left(\frac{\triangle f}{m}\right)'}$

Hence, the expansion work $= F\dfrac{\Sigma(\triangle f)'}{m_0'} = F\Sigma\left(\dfrac{\triangle f}{m}\right)$

Average scale of the compression work: $m_0'' = \dfrac{\Sigma(\triangle f)''}{\Sigma\left(\frac{\triangle f}{m}\right)''}$

Hence, the compression work $= F\dfrac{\Sigma(\triangle f)''}{m_0''} = F\Sigma\left(\dfrac{\triangle f}{m}\right)''$

Therefore, the indicated work $= F\left\{ \Sigma\left[\dfrac{\triangle f}{m}\right]' - \Sigma\left[\dfrac{\triangle f}{m}\right]'' \right\}$ or

$$F = \frac{\Sigma(\triangle f)' - \Sigma(\triangle f)''}{M_0}$$

Where M_0 denotes the average scale for the whole diagram.

$$\text{Then, } M_0 = \frac{\Sigma(\triangle f)' - \Sigma(\triangle f)''}{\Sigma\left[\frac{\triangle f}{m}\right]' - \Sigma\left[\frac{\triangle f}{m}\right]''}$$

The application of these methods produced the results shown in the following table:

The ratio of the areas of the indicator pistons amounted from exact measurements by means of micrometers to 4.025, and, hence, the mean scales to be substituted for the solution of work are:

With full load.	With half load.
$M_0 = 0.999$ mm. per 1 kg.	$M_0 = 1.006$ mm. per 1 kg.

With sufficient accuracy we can write

$$M_0 = 1 \text{ mm. per } 1 \text{ kg.}$$

WORKING CYLINDER.

	Full Load.					Half Load.			
	Expansion.			Compression.		Expansion.		Compression.	
	Scale millim.	$\Delta f'$ sq. mm.	$\frac{\Delta f'}{m}$	$\Delta f''$ sq. mm.	$\frac{\Delta f''}{m}$	$\Delta f'$ sq. mm.	$\frac{\Delta f'}{m}$	$\Delta f''$ sq. mm.	$\frac{\Delta f''}{m}$
1	4.30	90	20.9	80	18.6	90	20.9	90	20.9
2	4.29	140	32.6	50	1.6	130	30.3	30	7.0
3	4.13	120	29.0	40	9.6	80	19.4	50	12.1
4	4.06	80	19.7	30	7.4	70	17.3	30	7.4
5	3.99	80	20.0	30	7.5	60	15.0	40	10.0
6	3.96	100	25.2	30	7.6	100	25.2	50	12.8
7	3.85	200	52.0	30	7.8	100	26.0		
Total......		810	199.4	290	70.1	630	154.1	290	70.2
Mean scale.		$\frac{810}{199.4} = 4.06$		$\frac{290}{70.1} = 4.14$		$\frac{630}{154.1} = 4.08$		$\frac{290}{70.2} = 4.13$	
Total scale.		$\frac{810 - 290}{199.4 - 70.1} = 4.02$				$\frac{630 - 290}{154.1 - 70.2} = 4.05$			

AIR PUMP CYLINDER.

	Full Load.					Half Load.			
	Compression.			Expansion.		Compression.		Expansion.	
	Scale millim.	$\Delta f'$ sq. mm.	$\frac{\Delta f'}{m}$	$\Delta f''$ sq. mm.	$\frac{\Delta f''}{m}$	$\Delta f'$ sq. mm.	$\frac{\Delta f'}{m}$	$\Delta f''$ sq. mm.	$\frac{\Delta f''}{m}$
1	4.10	60	14.6	——	——	70	17.1	——	——
2	4.09	50	12.2	30	7.3	50	12.2	40	9.8
3	4.01	40	10.0	(m =	——	40	10.0	(m =	——
4	3.98	20	5.0	4.1)	——	20	5.0	4.1)	——
5	3.92	20	5.1	50	12.5	20	5.1	60	15.0
6,7,8,	2.88	70	18.0	(m =	——	70	18.0	(m =	——
9	3.89	100	35.8	4.0)	——	110	28.4	4.0)	——
Total......		360	90.7	80	19.8	380	95.8	100	24.8
Mean scale.		$\frac{360}{90.7} = 3.97$		$\frac{80}{19.8} = 4.04$		$\frac{380}{95.8} = 3.96$		$\frac{100}{24.8} = 4.03$	
Total scale.		$\frac{360 - 80}{90.07 - 19.8} = 3.95$				$\frac{380 - 100}{95.8 - 24.8} = 3.945$			

The investigation included full and half load, and in addition to that original diagrams were taken during the action of the governor. They showed a very great regularity of the combustion process; one hundred and more diagrams were found to coincide exactly, just as with steam-engines, a proof of the regularity of the process of working in the cylinder. Diagrams for full and half load were selected at random, and with their corresponding air-pump diagrams, are represented in Figs. 13 to 16; the several periods of the process can be distinctly observed.

As to the calculation of the indicated work, the difference between the motor and pump diagram is to be considered as such, for the latter represents in its upper limit-line the expansion work of the quantities of air which came from the working cylinder and the air-pump respectively. Their corresponding compression work is to be found partly in the motor and partly in the air-pump diagram; in the former the area covered by the compression curve represents the work, in the latter the total area of the diagram. Taking into consideration the average scales given above, we obtained the following compilation of the average mean pressures of all diagrams, taken during one hour's running of the engine. The indicated work was calculated from the number of constant revolutions during the trials by means of tachometers:

		Full Load.		Half Load.	
Number of trial		I.	II.	III.	IV.
Mean number of revolutions per min		171.8	154.2	154.1	158.0
Working Cylinder	Mean ind. pressure, kg. per sq. c. m.	7.44	7.38	5.28	5.15
	Ind. work done	27.85	24.77	17.71	17.72
Air Pump	Mean ind. pressure, kg. per sq. c. m.	4.38	4.45	4.32	4.43
	Ind. work done	1.29	1.17	1.14	1.20
Total indicated work done		26.56	23.60	16.57	16.52

In addition it *must be* noted that the governor was disconnected during one trial in order to obtain as constant ratios as possible. The variation in the number of revolutions from one trial to the other was effected every time by again connecting the governor. During the first trial a number of revolutions were purposely chosen above the average.

It is of interest at this time, with the motor working at such high pressures, to examine the ratio between the effective positive work and the negative indicated work.

From the mean diagrams, which were used for the calculation of the mean scales, the following values were obtained:

Manner of operation.	Total positive (expansion) work. H. P.		Total negative (compression) work. H. P.		Ratio, $\frac{\text{negative}}{\text{positive}}$ work.
	I	II	I	II	Average.
Full load	46.6	41.5	20.2	17.9	0.43
	Average between III and IV.		Average between III and IV.		
Half load	34.8		18.3		0.52

The slight differences between the values of the indicated total work, as shown by this table and that previously referred to, are due to the fact that with the latter the average scales were taken from all diagrams, but in the former, on the contrary, they were calculated from one diagram only.

II. EFFECTIVE WORK DONE.

Brauer's brake was attached to the flywheel, the loading weight in the scale acting on the circumference by means of a rope and roll. The constants of the brake figured by weighing and measuring were:

Length of lever.................... $l = 1274$ mm.
Weight of scale, rope included, $W = 10$ kg.
Constant.................... $\frac{l \times \pi}{3075} = 0.0017788$

The figures obtained by observation and the result obtained from them are contained in the following table:

Number of trial	I.	II.	III.	IV.
	Full load.		Half load.	
Mean number of revs. per min.	171.8	154.2	154.1	158.0
Total load at the brake, kg.	65	65	35	35
Effective work done, hp.	19.87	17.82	9.58	9.84
Indicated work done, "	26.56	23.60	16.57	16.52
Mechanical efficiency, per cent.	74.8	75.5	57.5	59.6

That the efficiency $\frac{N_e}{N_i}$ decreases with small loads is a peculiarity common to all motors, but by establishing, during full work done at from 18 to 20 horse-power, a mechanical efficiency of 75 per cent., all fears on that point are allayed. I only regret that it was impossible to set up the motor here at Cassell, and to present it to you while running; all who worked on the motor's development were astonished at the extreme simplicity and easiness of starting it. It may be mentioned that the way it ran, as well as the safety and uniformity of running, did not suggest to the observers an idea of the immense forces contained in the motor.

III. CONSUMPTION OF PETROLEUM.

The petroleum used during the test was taken from a can which was weighed before and after the trial on a carefully constructed scale. Before starting and beginning the trial the motor was supplied with petroleum from a second can, filled from the same storage barrel. A very simple but reliable contrivance at a given signal shut off the supply from the one can and started that from the second can. The same manipulation was performed backward toward the end of the trial. The results were the following:

	Full load.		Half load.		Idle running.
Number of trial	I.	II.	III.	IV.	V.
	60	60	60	60	31
Gross weight oil can before trial.	20.00	15.08	20.00	17.34	13.61
" " " after "	15.08	10.84	17.34	14.62	12.64
Consump. petroleum per hour	4.92	4.24	2.66	2.72	1.88
Effective work done	19.87	17.82	9.58	9.84	——
Consump. petroleum p. eff. hp.-hr.	0.247	0.238	0.278	0.276	——
" " p. ind. "	0.185	0.180	0.161	0.165	——

Thereby is proven that the motor in its present state and in its first construction far surpasses all other petroleum motors, showing at normal revolutions and full load the very low consumption of 240 grams per effective horse-power hour. A peculiarity, furthermore, to be considered is the very low increase of the relative consumption, if the load is reduced to one-half, whereby the consumption only increases 15 per cent. above that when at full work. Finally, the consumption during idle running is also lower than that of all other petroleum motors, as is shown by the graphical representation in Fig. 10. In this the displacement per liter and effective horse-power per second are laid off as abscissae, and the consumption of petroleum per hour and effective horse-power as ordinates. This diagram has been drawn by Professor Hartmann, according to his trials and those of the Diesel motor. One glance at the figure is sufficient to comprehend the progress represented by the motor in both directions. The great superiority in view of the consumption at half load is especially to be perceived—the reasons for it will be seen by the result from the heat balance-sheet accompanying this communication. The advantage of small dimensions, and its influence upon displacement per second per effective horse-power, is yet more conspicuous, if we compare the diagram of a steam-engine (ocean greyhound "Fürst Bismarck"), a petroleum motor and the Diesel motor drawn in the same scale; in all three cases the figure is based on a diagram actually taken (Fig. 9).

		I.	II.	III.	IV.
Mean temp. of cooling water at inlet, C°		9.83	9.62	9.1	9.35
" " " " " outlet, C°		24.26	20.28	18.26	21.49
Mean heating of cooling water		14.43	11.66	9.16	12.14
Mean temperature of exhaust gases		404	378	260	260
Mean over-pressure in air vessel, kg. p.sq.cm.		41.0	42.7	39.6	39.5
Quantity of cooling water.	1. observation; liters p. hr.	1286	1738	1350	957
	2. " " "	1190	1820	1307	980
	3. " " "	1333	1465	1345	1070
	4. " " "	1786	1564	——	——
Heating of cooling water during period of observation (mean values).	1. C°	16.2	10.6	9.57	10.8
	2. "	16.1	9.9	9.0	12.5
	3. "	13.9	10.9	8.97	12.6
	4. "	11.1	11.1	——	——
Heat transmitted to cooling water.	1. calories per hour	20820	18840	12920	10340
	2. " " "	19160	18020	11770	12250
	3. " " "	18550	15970	12060	13480
	4. " " "	19880	17360	——	——
Average		19580	17450	12250	12030

IV. MEASUREMENT OF TEMPERATURE AND COOLING WATER.

Thermometers, which had been tested at the Royal Institute of Technical Physics, were used for measuring the temperature. The temperature of the expelled gases was measured immediately behind the emission valve and that of the cooling water before entering and immediately before leaving the cooling jacket. It was only possible to measure the quantity of cooling water periodically and not continually, by observing the time needed for filling a measure of 200 liters or 7 cubic feet capacity; by simultaneously reading the temperature, one obtained the heat transmitted to the cooling water during the period of observation. As the apparatus was occasionally regulated, no constant value could be obtained; especially was this the case in the second trial. It must be stated that during the trials very low temperatures were observed; the wall of the working cylinder was so cool that a thermometer, covered with cotton, put very close to it showed a temperature only 5° to 6° C. below that of air. A little reduction was observed only at the cylinder cover. The table on preceding page contains the mean values:

V. ANALYSIS AND DETERMINATION OF THE CALORIFIC VALUE OF THE PETROLEUM.

a. Specific Gravity.

During the trials the specific gravity of the petroleum in the can, as well as that in the storage barrel, was several times ascertained. In order to compare the acquired values it was necessary to transform them to the normal temperature of 12° R, for which purpose the reduction table of Veith was used.

The specific gravity of the oil was determined as follows:

From the can.	1) at 29.5°C....g = 0.786	at 12°R....g = 0.7953
	2) at 25.7°C....g = 0.788	at 12°R....g = 0.7955
	3) at 24.0°C ...g = 0.7895	at 12°R....g = 0.7957
		Average = 0.7955
From storage barrel	1) at 19.8°C....g = 0.792	at 12°R....g = 0.7955
	2) at 20.0°C....g = 0.793	at 12°R....g = 0.7965

The first four determinations were produced with the same areometer and proved the entire similarity of the petroleum in both vessels. The latter determination was effected with another areometer, and, therefore, the small deviation is explained.

b. Elementary Analysis.

Two analyses which checked perfectly are here given:

I. 0.5187 gram of petroleum gave 1.6188 gr. CO_2.
and 0.6648 gr. H_2O.

II. 0.2896 gram of petroleum gave 0.9042 gr. CO_2.
and 0.3697 gr. H_2O.

This gives the following composition:

I.	II.	Average.
85.11 per cent. C.	85.15 per cent. C.	85.13 per cent. C.
14.24 " H.	14.18 " H.	14.21 " H.
0.65 " O.	0.67 " O.	0.66 " O.

CALORIFIC VALUE OF THE PETROLEUM USED IN THE TESTS.

	From the can.			From the storage tank.	
	1.	2.	3.	4.	5.
1. Weight of petroleum burnt in calorimeter	3	15	10	10	10
2. Quantity of cooling water	1990	9600	7270	6430	6570
3. Water from condensation	3.8	21	14.5	14	14
4. Outside temperature	20.9	19.6	20.0	19.6	19.2
5. Temperature of exhaust-gases	17	17.5	17.5	17.5	17.5
6. Temperatures of cooling water (mean values)	Inlet 9.65 Outlet 26.135	Inlet 9.584 Outlet 26.758	Inlet 9.5 Outlet 24.796	Inlet 9.6 Outlet 26.763	Inlet 9.683 Outlet 26.228
7. Heating of cooling water	16.485	17.174	15.296	17.163	16.545
8. Highest heat value $= \frac{\text{value } 7 \times \text{value } 2}{\text{Value } 1}$	10935.05	10991.36	11120.19	11035.8	10870.06
9. Condensation-heat of vaporized water	784.07	866.60	897.55	866.6	866.6
10. Lowest heat value	10150.98	10124.76	10222.64	10169.2	10003.46
11. Average			10134.2		

Fractional distillation in Engler's apparatus gave:

Fraction from 100 to 150° C. = 15.0 cubic c. m.
“ “ 150 “ 175° “ = 8.8 “ “
“ “ 175 “ 200° “ = 10.2 “ “
“ “ 200 “ 225° “ = 9.0 “ “
“ “ 225 “ 250° “ = 10.0 “ “
“ “ 250 “ 275° “ = 10.2 “ “
“ “ 275 “ 300° “ = 11.8 “ “
“ over “ 300° “ = 25.0 “ “
100 “ “

From the great amount of high boiling oils being contained in it we must conclude that American petroleum was present.

c. Determination of the Calorific Value of the Oil.

1. By Junker's Calorimeter.

This indispensable apparatus proved itself very successful for petroleum in the arrangement adopted by Mr. Diesel, and which is the same as that which Junker himself recently used. During the test a great number of observations were made, a record of which is given in the accompanying table.

2. By Mahler's Bomb Calorimeter.

In order to combine the values already satisfactorily agreeing, two more experiments were performed in the laboratory of the Technical College at Munich with Mahler's bomb, the most successful modern apparatus for ascertaining calorific values, and as the publication of the complete results thereon would take up too much space it may be mentioned that both tests agreed pretty well and resulted in the following values:

Lowest heating value.......	*a*	*b*	average
Calories per kg.............	10264.6	10291.9	10277.9

From this we obtain the mean value,

$$\frac{10277.9 + 10134.2}{2} = 10206 \text{ calories}$$

which was assumed as the lowest heating value per 1 kg. (2.2 lbs) of petroleum.

VI. HEAT DISTRIBUTION OF THE MOTOR.

From the foregoing statements this may be expressed as follows:

HEAT DISTRIBUTION DIESEL'S MOTOR PER HOUR.

	Full Load.				Half Load.			
	Absolute.	Per cent.	Absolute.	Per cent.	Absolute.	Per cent.	Absolute.	Per cent.
Disposable heat (in calories)..	50213	100	43273	100	27148	100	27760	100
Equivalent in indicated work..	16913	33.7	15028	34.7	10552	38.9	10520	37.9
Transmitted to cooling water.	19580	39.0	17450	40.3	12250	45.1	12030	43.3
Remainder......................	13720	27.3	10795	25.0	5346	16.0	5210	18.8
Equivalent in effective work..	15653	25.2	11348	26.2	6100	22.5	6266	22.6

Although the excessive number of revolutions was the cause of the somewhat low efficiency during the first trial, the arithmetical mean of both loads may be considered the final result, as the following table shows:

PERCENTAGE OF DISPOSABLE HEAT.

Manner of operation	Full Load.	Half Load.
Converted into indicated work	34.2	38.5
" " effective "	25.7	22.4

These figures state the final result of the investigation and characteristic of Diesel's motor as well. This motor in its first form of construction must, therefore, be put at the head of all caloric motors known, in view of its thermal efficiency, as it indicated at full work 34.2 per cent. and at half work, 38.5 per cent. of the whole heat contained in the fuel. That is a splendid triumph of theory which could not be anticipated,considering that to the present development of the idea there is still more to add, as the motor stands only at the beginning of its development, and higher values are yet to be obtained.

Before evaluating the Diesel motor, according to figures referred to, I will mention another important investigation, which is necessary to complete the description.

VII. TESTING OF THE EXPELLED GASES.

In the pipe carrying away the expelled gases a small metal pipe was fitted in such a manner that a short piece of it projected within the exhaust pipe, thus permitting only a portion of the expelled gases to exhaust through a copper spiral connected with this small pipe. The gases were tested by means of cylindrical glass vessels, closed below and above by cocks, connected with a recipient filled with glass-wool. The vessel entirely filled with water was immersed into a larger water vessel, and the cocks having been opened, gas was for a long time allowed to enter into and flow through it. The collecting under water was under all circumstances necessary to positively avoid the entrance of air. At a previous trial the gas exhausting was conducted for a long time, through the usual gas wash-bottle half filled with water. After a fifteen minute passage of the most violent gas-flow it was not possible to detect the least separation of oil particles in the watery fluid, and the latter gave off only a very weak petroleum smell; the perfect combustion was thus indicated.

Hempel's burette and gas-pipette filled with the usual absorption materials served for the chemical testing. The research was also extended to heavy hydro-carbons, hydrogen and methane, which, however, was without any success; the composition is shown in the following table.

Although the amount of CO was already very small at full work, it entirely disappeared at half work. At full work light steam vapors were to be seen at the end of the exhaust pipe, which disappeared altogether at half work; the exhaust was entirely invisible and its gases nearly odorless. From the composition of the gaseous portion of the combustion products a conclusion may be derived as to the quantity of surplus air. If the combustion products consist of R—per cent. by volume CO_2, O per cent. by

COMPOSITION OF EXHAUST GASES. PERCENTAGE BY VOLUME.

Kind of Gas.	Full load.						Half load.				
	1.	2.	3.	4.	5.	average	1.	2.	3.	4.	average
Co$_2$	10.0	9.8	10.0	10.2	9.8	9.96	6.2	5.9	5.9	5.8	5.95
O	5.0	4.7	4.6	4.6	4.6	4.70	11.8	11.7	11.7	11.8	11.75
CO	0.2	0.1	0.3	0.2	0.2	0.20	0	0	0	0	0
N	84.8	85.4	85.1	85.0	85.4	85.14	82.0	82.4	82.4	82.4	82.30

volume of O, and N—per cent. by volume of N, the surplus air contained $\frac{79}{21}\,O$ parts of N. By subtracting this calculated N from the total N of the combustion air, we obtain that quantity of N which was admitted with the really consumed air, *i. e.*, $N - \frac{79}{21}O$. The ratio of the entire quantity of air admitted to that really consumed (or theoretically necessary) being the same as that of both quantities of N, we obtain the so-called surplus co-efficient

$$u = \frac{\text{Total admitted}}{\text{Actually consumed}} \text{ quantity of air} = \frac{N}{N - \frac{79}{21}O} = \frac{21}{21 - 79\frac{O}{N}}$$

This very well known relation gives us the following values:

	Full Load.	Half Load.
1	1.285	2.180
2	1.262	2.147
3	1.255	2.147
4	1.256	2.168
5	1.254	——
Average	1.262	2.160

As was to be anticipated from the construction of the engine, at half work proportionally more air has been admitted than at full work.

The theoretically least quantity of air is to be found from the chemical composition of the petroleum according to the formula:

$$L = ({}^{3}\!/\!{}_{8}\ C + H - O)\frac{100}{23} = (\frac{8}{3}0.8513 + 8 \times 0.1421 - 0.0066)\frac{100}{23} =$$

14.7839 kg., per 1 kg. petroleum.

As with perfectly conducted combustion, 1 kg. C is combined with $\frac{8}{3}$ kg. O to form 3.667 kg. CO_2 and 1 kg. H with 8 kg. O to form 9 kg. H_2O, the exhaust gases of the consumed petroleum, provided perfect combustion is effected, will have the following composition:

$$0.8513 \times 3.667 = 3.1214 \text{ kg. } CO_2$$
$$\text{and } 0.1421 \times 9 = 1.2789 \text{ kg. } H_2O.$$